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Theory and Simulation of Resonant Magnetic Perturbations*

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One of the most important needs at the forefront of tokamak fusion science is to understand the optimal control of three-dimensional (3D) magnetic fields that perturb the axisymmetric (2D) equilibrium [1-2]. Generating the physical understanding needed for future tokamak reactors challenges the present state of the art in high performance computational science and requires the development and implementation of new theoretical and computational approaches.

Resonant magnetic perturbations (RMPs) generate a drive for magnetic reconnection by exciting harmonics with the same pitch as the equilibrium magnetic field, so that their parallel wavenumber vanishes on a series of resonant flux surfaces. Complete reconnection on neighboring resonant surfaces can potentially lead to drastic changes in the topology of the equilibrium field by generating magnetic islands that overlap to form ergodic regions. Naturally occurring instabilities that lead to reconnection are responsible for many of the major transient phenomena in a tokamak: sawteeth, neoclassical tearing modes, and locked modes, which can lead to disruptions. Yet externally generated RMPs can also be used to control transport, drive current and torque, and perhaps surprisingly, to control edge localized modes (ELMs) in high-confinement mode (H-mode) through the control of edge transport, reviewed in [3]. For example, a fluid simulation [4] of an RMP-induced ergodic edge region generated by external coils used to control ELMs is compared to measurements of edge Dα emission on the DIII-D tokamak in Fig. 1. Thus, learning to tailor the RMP spectrum may be even more important than suppressing error fields.

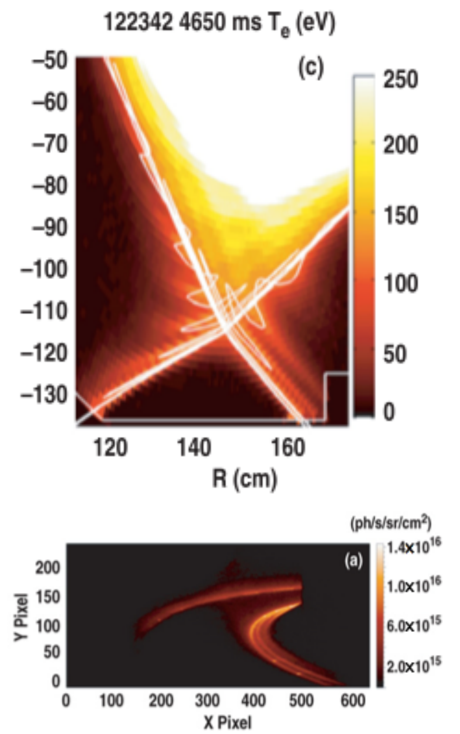

Figure 1: RMPs can be used to control plasma-wall interactions via generation of an "ergodic" divertor, as simulated in (a). Accurate prediction of measurements shown in (b) for DIII-D discharge 123301 requires self- consistent models of plasma response and shielding processes. (From Ref. [4])

The computational challenges arise from the fact that, since a high temperature fusion-grade plasma is a nearly perfect conductor, the conservation of magnetic flux implies that externally generated RMP fields must be precisely shielded by currents flowing near the spatial location of the resonance [1,2]. The structure of the narrow current layer near the shielding region is typically microscopic relative to the scale length of the perturbation fields and can be rather complex depending on the physics of the dissipative and kinetic processes at play. For example, in a resistive model, both the width of the current layer and the amplitude of the internal field depend on inverse powers of the magnetic Reynolds (Lundquist) number, which routinely exceeds 10^9 at the edge of an H-mode tokamak. Yet, once dissipative scales fall below the ion gyroradius, kinetic effects must be included: the ion response is limited by their microscopic Larmor motion around magnetic field lines, while the electrons are free to respond on much smaller scales. The combined plasma response crucially depends on the manner in which the electromagnetic Lorentz torque associated with the perturbation is balanced by inertial and viscous torques generated by plasma rotation [1-2]. Analytical models of the two-fluid plasma dynamics, shown in Fig. 2, predict that the internal response to an external perturbation is largest when the relative rotation between the perturbation phase and the plasma is near particular frequencies, such as the electron diamagnetic frequency. Thus, the response is especially sensitive to the differential rotation of the ion and electron species and to the kinetic viscous forces that damp these flows in the presence of perturbations.

Theoretical and numerical algorithms need to be developed that efficiently address the multi-scale and multi-physics challenges of simulating kinetic reconnection processes in fusion plasmas in time and in (5D-6D) phase space. Achieving the required resolution implies that the equations must be solved using massively parallel high-performance scientific computing architectures. Numerical techniques that must be utilized include preconditioned implicit solvers and adaptive mesh resolution. Next generation models require the capability to predict nonlinear RMP effects and their use in controlling instabilities in realistic geometry. The essential challenge in phase space is that there are a number of invariants that are nearly conserved, but where the conservation laws are broken, the topology of phase space becomes extremely complex. In these cases, transport cannot be accurately computed using fluid models, but must be addressed with models that incorporate kinetic effects. Systematic approaches, such as nonlinear gyro-Landau fluid models, have the potential to bridge the gap between fluid (3D) and kinetic (5-6D) models while minimizing computational cost.

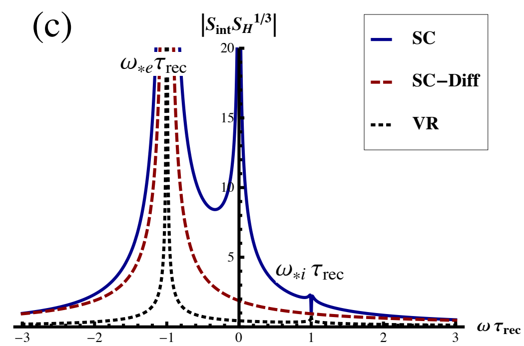

Figure 2: The ratio between the internal RMP amplitude and the externally applied amplitude for three different analytic models. The result crucially depends on the rotation of the plasma relative to the diamagnetic frequency ω_* (From Ref. [3].)

Ultimately, utilizing and controlling 3D fields will achieve a synthesis of our understanding of tokamaks with that of quasi-axisymmetric devices, which combine the excellent confinement of a 2D tokamak with the design flexibility of a 3D stellarator. Thus, developing the fundamental physics understanding of 3D magnetic fields needed today will make bold strides toward the future of fusion science.

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